



PROTON TRANSFER REACTION STUDIES

An Investigation of Properties of Excited
Levels in Particular Isobaric Analogue
States in ^{28}Si , ^{55}Co and ^{60}Ni .

JACQUETTE LYTTKENS



LUND 1976

PROTON TRANSFER REACTION STUDIES

An Investigation of Properties of Excited Levels
in Particular Isobaric Analogue States in ^{28}Si ,
 ^{55}Co and ^{60}Ni .

Jacquette Lyttkens

Fil mag, Ld

Akademisk avhandling som för avläggande av filosofie
doktorsexamen vid matematisk-naturvetenskapliga
fakulteten vid universitetet i Lund kommer att
offentligen försvaras i fysiska institutionens
föreläsningssal B fredagen den 21 maj 1976 kl 10.15.

PROTON TRANSFER REACTION STUDIES

An Investigation of Properties of Excited Levels
in Particular Isobaric Analogue States in ^{28}Si ,
 ^{55}Co and ^{60}Ni .

by

Jacquette Lyttkens

PROTON TRANSFER REACTION STUDIES

An Investigation of Properties of Excited Levels
in Particular Isobaric Analogous States in ^{18}O

by
J. G. and G. M.

Jaeger, J. G.



SUMMARY

This thesis comprises the following papers:

- I ISOMERIC ANALOGUE STATES INDUCED IN THE $^{55}\text{Fe}(p,\gamma)^{56}\text{Co}$ REACTION,
(together with A. Brinkman and A. Haxel)
Delft University of Technology Report (1975) 97.
- II THE $^{55}\text{Fe}(p,\gamma)^{56}\text{Co}$ REACTION AND BOUND ISOMERIC ANALOGUE STATES IN ^{56}Co ,
(together with A. Brinkman, G. Lohse and A. Haxel)
Delft University of Technology Report (1975) 99.
- III ^{55}Co LEVEL PROPERTIES
(together with G. Lohse, A. Haxel and A. Brinkman)
TNO 91/75, TNO Laboratory Report, Utrecht, 1975.
Accepted for publication in Physics Letters.
- IV EXCITED LEVELS AND ISOMERIC ANALOGUE STATES IN ^{55}Co INVESTIGATED WITH THE $^{54}\text{Fe}(p,\gamma)^{55}\text{Co}$ REACTION,
(together with A. Brinkman)
TNO 76/76, TNO Laboratory Report, Delft University,
1976.

Introduction

The concept of isomerism was introduced in order to describe the nucleus and proton as alternative states of nuclear energy. The nucleus is a system of nucleons and

TO MY PARENTS



Digitized by the Internet Archive
in 2026

https://archive.org/details/IA41553216_0038

SUMMARY

This thesis comprises the following papers:

- I ISOBARIC ANALOGUE STATES EXCITED IN THE $^{59}\text{Co}(p,\gamma)^{60}\text{Ni}$ REACTION,
(together with B Erlandsson and A Marcinkowski)
Zeitschrift für Physik A272 (1975) 67.

- II THE $^{27}\text{Al}(d,n\gamma)$ REACTION AND BOUND ISOBARIC ANALOGUE STATES IN ^{28}Si ,
(together with I Bergqvist, G Lodin and L Nilsson)
Physica Scripta 13 (1976) 96.

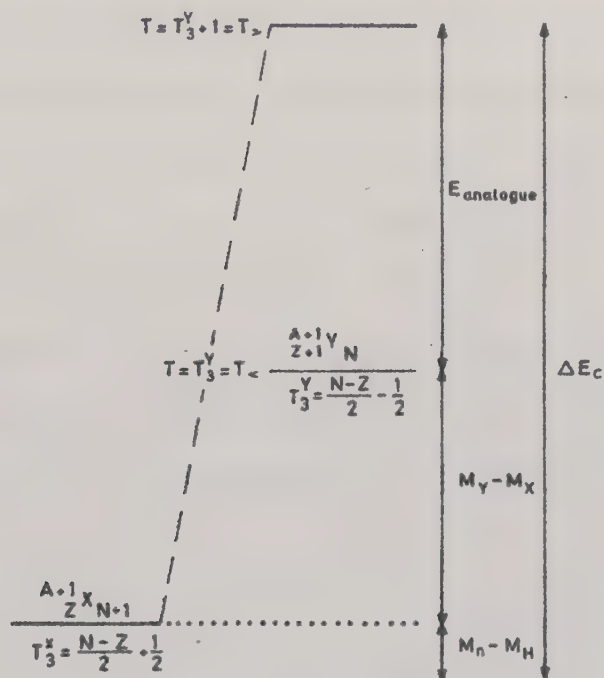
- III ^{55}Co LEVEL PROPERTIES
(together with G Lodin, L Nilsson and B Erlandsson)
TLU 41/75, Tandem Laboratory Report, Uppsala 1975.
Accepted for publication in Physica Scripta.

- IV EXCITED LEVELS AND ISOBARIC ANALOGUE STATES IN ^{55}Co INVESTIGATED WITH THE $^{54}\text{Fe}(p,\gamma)^{55}\text{Co}$ REACTION,
(together with B Erlandsson)
LUNP 7604, Nuclear Physics Report, Lund University,
1976.

Introduction

The concept of isospin was introduced in order to describe the neutron and proton as alternative states of the nucleon. The nucleon is assigned isospin $T = 1/2$ and values of the

third components $T_3 = +1/2$ and $-1/2$ then denote the neutron and proton respectively. The formalism is developed in the same way as for ordinary spin. If the nuclear force is charge independent, i.e. the n-p, p-p and n-n interactions are equal, then the isospin T is a good quantum number.



A nucleus with mass number A , consisting of Z protons and N neutrons, has a third component of the isospin $T_3 = (N-Z)/2$ and ground state isospin equal to the third component. When it reacts with a proton with isospin $t = 1/2$ and third component $t_3 = -1/2$, the final nucleus ${}^{A+1}_{Z+1}Y_N$ (see figure) will have $T_3^Y = T_3 + t_3 = (N-Z)/2 - 1/2$. The isospins can either be parallel and couple to $T + 1/2$ which is denoted T_+ ("T upper") or be antiparallel and couple to $T - 1/2$ which is denoted T_- ("T lower"). The

nucleus ${}^{A+1}_{Z}X_{N+1}$ has $T_3^X = (N-Z)/2 + 1/2$ and the states in nucleus Y with isospin $T_>$ correspond to states in X. They are called isobaric analogue states (IAS) and the levels in X are called parent states. The situation can be compared to a neutron-induced reaction in which the third component of the isospin is raised by 1/2 and consequently only states with isospin $T_>$ can be populated ($T \geq |T_3|$).

The Coulomb interaction influences the position of the analogue states and the Coulomb displacement energy, ΔE_c , is defined as the energy difference between the analogue and parent states due to the addition of unit charge (see figure). It is equal to the Q-value of a (p,n) reaction between the nuclei except for the sign. It is an interesting property since it can both be measured experimentally and calculated (1). A semiempirical formulae gives (1,2)

$$\Delta E_c = b_1 \frac{\bar{Z}}{A^{1/3}} + b_2$$

where $\bar{Z} = (Z_1 + Z_2)/2$. This is with few exceptions correct to within ± 100 keV. For $Z > 20$ or $N > 20$, Jänecke (1) gives $b_1 = 1430$ keV and $b_2 = -992$ keV.

IAS have a simple structure compared to their neighbours, $T_<$ states, since they correspond to low-lying levels in the parent nucleus. They therefore stand out as strong peaks in (p, γ) yield curves and in (d,n) spectra. With the (p, γ) reaction, IAS which are unbound with respect to proton emission can be populated directly and bound IAS only secondarily. As relatively high-lying bound levels are hard

to populate secondarily, they can preferably be studied using $(d, n\gamma)$ or $(^3\text{He}, d\gamma)$ reactions. The (p, γ) and the $(d, n\gamma)$ reactions complement each other nicely and they have both been used in the study of ^{55}Co (papers III and IV).

The proton and the target nucleus can also combine to a state with the same configuration as the isobaric analogue state but with isospin $T_<$. This is the so-called "anti-analogue state". The energy difference between analogue and anti-analogue states is supposed to be $E_{T_>} - E_{T_<} = (T_0 + \frac{1}{2})V_1/A$ (3), where V_1 is about 100 MeV in the $1f_{7/2}$ shell and T_0 is the isospin of the target nucleus. Shell-model calculations give strong M1-transitions between analogue and anti-analogue states and such have, in fact, frequently been observed in the $2s_{1/2}$ shell (4). On the other hand, core polarization effects have been found to reduce the strength in odd-A nuclei, especially for $j = l + \frac{1}{2}$ particles (5).

Experimental procedure

The (p, γ) experiments (papers I and IV) were performed at the 3 MeV Van de Graaff generator in Lund. The coincidence yield curves were recorded with two NaI(Tl) detectors at 90° to the beam, opposite each other. Otherwise, the gamma rays were detected by Ge(Li) spectrometers. For branching-ratio measurements, a detector was positioned at 55° to the beam and for energy determinations at 90° . The gamma-ray

spectra were analyzed with the computer programme ANNLIIS (6) which automatically locates peaks and calculates their positions and areas. Composite peaks were resolved by least-squares fits of skewed gaussians with the programme GAUSS (7).

The (d,n γ) experiments (papers II and III) were performed at the 6 MV tandem accelerator in Uppsala with a pulsed deuteron beam. The neutrons were detected by a 5.1 cm x x 30.5 cm NE 213 liquid scintillator placed at 0° to the beam. Thus, the conditions of Method II of Litherland and Ferguson (8) were fulfilled, which means that branching ratios measured with the gamma detector at 55° or 125° are correct as long as quadrupole radiation can be neglected. Data from coincidences between neutrons and gamma rays were collected event by event on magnetic tape with an "on-line" computer. Gamma-ray spectra corresponding to selected neutron energy intervals were sorted out "off-line" and analyzed.

Results and discussion

In paper I the decay of ten resonances in the $^{59}\text{Co}(p,\gamma)^{60}\text{Ni}$ reaction has been investigated. In ^{60}Ni transitions to the ground state are very weak and almost all decays proceed via the first excited state at 1332 keV. Therefore the intensity of the 1332 keV gamma ray is a good indicator of the total decay of the resonance. By comparison of this intensity with the observed decay to the bound levels from the resonance, it was found that at eight of the resonances

less than 40% of the decay was accounted for. The rest of the decay probably goes to levels in the energy region 5 - 9 MeV in ^{60}Ni . In the investigation 24 bound excited levels were populated from the resonant states and for all but two of these the decay was determined. The results were compared with two earlier reports (9,10) and in general the agreement was good.

Five of the resonances were identified as probable analogues of ^{60}Co levels. The semiempirical formula by Andersson et al. (2) gives $\Delta E_c = 9013 \pm 50$ keV which corresponds to $E_x = 11.0 - 11.5$ MeV for the ground state (5^+) analogue. From this analogue decay to levels with spin less than 3 should be almost out of the question. Therefore gamma-ray spectra were recorded at close intervals in the energy region of interest and the intensities of transitions to the low-lying 2^+ , 3^+ and 4^+ levels were studied. In the same way, the region of interest for the analogue of the 5^+ state at 435 keV in ^{60}Co was investigated. The levels at $E_x = 11155$ keV and 11597 keV were identified as the probable analogues. The ground state analogue gives a Coulomb displacement energy of 9118 ± 7 keV. In addition, the levels at $E_x = 11223$, 11427 and 11444 keV were suggested as analogues of the 2^+ state at 58.6 keV, the 4^+ state at 277.1 keV and the 3^+ state at 288.4 keV in ^{60}Co .

In ^{28}Si the lowest isobaric analogue states are bound and are therefore difficult to study with the (p,γ) reaction.

In paper II these levels have been studied with the $(d, n\gamma)$ reaction on ^{27}Al . As the neutrons were detected at 0° to the beam, $l_p = 0$ transitions are strong. The ground state of ^{27}Al has $J^\pi = 5/2^+$ and thus 2^+ and 3^+ levels in ^{28}Si are strongly populated, especially the analogues of the 3^+ ground state, 2^+ 1st excited state and $(2^+, 3^+)$ state at 2139 keV in ^{28}Al which also have fairly large spectroscopic factors. The first two analogues have been established (11) at 9316 and 9381 keV respectively. The analogue of the 2139 keV level was in paper II found to decay to the levels at 1779, 6277, 8589 and 9316 keV. The transitions to the 8589 and 9316 keV levels were used to determine the excitation energy of the analogue with the result 11434.1 ± 0.7 keV. In a (p, γ) work (12), which appeared during the publication of paper II, two levels with energies 11434.3 ± 1.0 keV and 11434.6 ± 1.5 keV are reported to be populated from different resonances. The first one is said to decay 100% to the 1779 keV level and the second one to the other three levels. Thus it seems probable that both levels were populated in the $(d, n\gamma)$ experiment.

The properties of levels in ^{55}Co are discussed in papers III and IV. As was the case in ^{28}Si , the low-lying isobaric analogue states in ^{55}Co are bound with respect to proton emission and are consequently best studied by the $(d, n\gamma)$ or the $(^3\text{He}, d\gamma)$ reactions, while the unbound analogues are preferably examined with the (p, γ) reaction. The decay of the bound $T_{\leq}$ states was deduced from a comparison of the results from the (p, γ) and $(d, n\gamma)$ experiments. The gamma

spectra from the $(d,n\gamma)$ experiment provide positive identification of the transitions, whereas the (p,γ) spectra yield many transitions and reasonably good statistics.

In the $(d,n\gamma)$ experiment, three levels at 4720, 4747 and 5172 keV were strongly populated. The 5172 keV level has earlier been identified (13) as the analogue of the 1:st excited state in ^{55}Co , in agreement with our results. Comparison between neutron transfer reactions to the ^{55}Fe ground state and proton transfer reactions to a level at 4.74 MeV in ^{55}Co led to an identification of the latter as the ground state analogue. Recently, however, particle- γ coincidence experiments have shown that the 4.74 MeV level is in fact a doublet. For the lower member at 4720 keV, spin and parity have been determined to be $3/2^-$ and it has been identified as the analogue (14). However, in our $(d,n\gamma)$ experiment, the 4720 and 4747 keV levels are almost equally strongly populated. Since T_{γ} states in this energy region are expected to have small spectroscopic factors, this led us to suggest that the ground state analogue is fragmented at least into the 4720 and 4747 keV levels.

In paper IV the decay of ten resonances in the $^{54}\text{Fe}(p,\gamma)$ yield curve is reported. Two of the resonances are established analogues of the levels at 2051 and 2144 keV in ^{55}Fe and three are possible analogues of the levels at 931, 1918 and 2469 keV. For four of the resonances, the angular distribution of the gamma rays was measured and spins or spin limitations were obtained for these resonances

and a number of bound levels. These measurements were also used to determine lifetimes with the Doppler Shift Attenuation Method. Because of the low recoil velocity (v/c typically 0.12%) a systematic error of 30% may be introduced in the lifetimes but nevertheless the agreement with results from ($^3\text{He}, d\gamma$) experiments is good. The strength $(2J+1)\Gamma_p\Gamma_\gamma/\Gamma$ was measured for six of the resonances. For the resonances at 1802 and 1886 keV, the results can be compared with Martin et al (15). Oddly, the results agree for $E_p = 1886$ keV whereas for $E_p = 1802$ keV our value is about half the value obtained by Martin et al.

REFERENCES

- 1) J Jänecke, Isospin in Nuclear Physics (ed D H Wilkinson), p 297, North-Holland Publ Co, Amsterdam 1969.
- 2) J D Andersson, C Wong and J W McClure, Phys Rev 138 (1965) B615.
- 3) A M Lane, Phys Rev Lett 8 (1962) 171.
- 4) P M Endt, Nuclear Structure (ed A Hossain et al), p 58, North-Holland Publ Co, Amsterdam 1967.
- 5) S Maripuu, Phys Lett 31B (1970) 181.
- 6) P Ekström, I Mauritzson and J Tillman, LUNP 7101, Nuclear Physics Report, Lund University 1971.
- 7) P Ekström, Ph D thesis, Lund University 1975.
- 8) A E Litherland and A J Ferguson, Can J Phys 39 (1961) 788.

- 9) D M Van Patter and F Rauch, Nucl Phys A191 (1972) 245.
- 10) H Ronsin et al, Nucl Phys A207 (1973) 577.
- 11) P M Endt and C van der Leun, Nucl Phys A214 (1973) 1.
- 12) M A Meyer, I Venter and D Reitmann, Nucl Phys A250 (1975) 235.
- 13) B Rosner and C H Holbrow, Phys Rev 154 (1967) 1080.
- 14) J R Leslie, D J Martin and W McLatchie, Phys Lett 36B (1971) 76.
- 15) D J Martin et al, Nucl Phys A187 (1972) 337.

ACKNOWLEDGEMENTS

My most sincere thanks are due to Drs Ingvar Bergqvist and Bengt Erlandsson. Through them my interest in nuclear spectroscopy was aroused and in the course of my work they have given me encouragement, good advice and inspiring cooperation.

Drs Leif Nilsson and Göran Lodin I want to thank for many valuable discussions and for their good spirits even during troublesome and tedious running periods. I am grateful that I have had the opportunity to work with them. I also want to thank Dr Andrzej Marcinkowski for a fruitful collaboration.

I am indebted to Dr Ragnar Hellborg, to Kjell Håkansson and Christer Nilsson for producing a beam out of the old Van de Graaff generator and to the members of the technical and

administrative staffs for aid in many ways.

I want to express my gratitude to the Tandem Accelerator Laboratory in Uppsala under Professor Arne Johansson, to Bengt Hemryd and the other members of the technical and administrative staffs and to Jörgen Pihl and László Gönczi who removed many problems with the computer system.

Finally, I wish to thank the members of the VdG "coffee group" for their support and friendship which have made these years so rich.

